

# Piloted Simulator Study of Allowable Time Delay in Pitch Flight Control System of a Transport Airplane With Negative Static Stability

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## Summary

A piloted simulation study was conducted to determine the permissible time delay in the flight control system of a 10-percent statically unstable transport airplane during cruise flight conditions. A joint venture between NASA Langley Research Center and the Lockheed-Georgia Company was conducted with the six-degree-of-freedom, ground-based Langley Visual/Motion Simulator (VMS). The math model used for the simulation represented a derivative Lockheed L-1011 wide-body jet transport. Both pure and first-order lag forms of time delay were inserted, at various locations, into the longitudinal flight control system, and their effects were evaluated by two engineering test pilots.

The pilots performed evaluation maneuvers that included precise pitch and roll attitude changes, airline operational turns, and wind-up turns from a nominal cruise flight condition (Mach = 0.83; Altitude = 33 000 ft). Data were collected and analyzed from a total of 137 cruising flights in both calm- and turbulent-air conditions.

Effective time-delay limits of approximately 0.17 sec for level 1 (satisfactory) flying qualities, 0.48 sec for level 2 (acceptable but not satisfactory) flying qualities, and 0.74 sec for level 3 (unacceptable but controllable) flying qualities were determined. Also, the degree of handling degradation due to time delay is shown to be strongly dependent on the source of the time delay in an advanced flight control system. Preliminary results also suggest that adverse effects of control-system time delay may be at least partially offset by variations in control gearing. These results suggest that the present military specifications governing allowable control system time delay may be too restrictive when applied to large transport-size airplanes.

## Introduction

The present military specifications (ref. 1) are generally recognized as being inappropriate in the designation of requirements and criteria for handling qualities of large class III (transport) airplanes. (See refs. 2, 3, and 4.) With the advent of fully powered, highly augmented control systems, lags introduced by the dynamics of the control system have become increasingly important. One area of concern is allowable time delays in aircraft response. Reference 2 tabulates the variation in the effective time delay for several large aircraft from past flight-test and ground-based simulation programs in the category C flight phase (approach and landing).

The airplane math model used in the reference 2 ground-based simulation study was a derivative of

the Lockheed L-1011 transport. The airplane modeled in reference 5 was an L-1011-500 with several different pitch active control systems (PACS), which allowed cruise flight at relaxed static stability (RSS) levels. These PACS had been developed during fuel-efficient transport studies in the early 1980's, and some were flight tested in conjunction with an active ailerons control system (AACS). The AACS allowed for reductions in wing-design loads by automatically moving the outboard ailerons symmetrically in response to accelerations sensed at the wingtips and in the fuselage. In addition to moving the ailerons symmetrically, the system moved the horizontal stabilizer automatically to compensate for the pitching moment produced when the airplane encountered a gust. The combination of AACS and a simple PACS (designated "near-term PACS" in ref. 5) was flight tested and was found to have satisfactory flying qualities at slightly negative static stability margins (up to 3 percent).

Another PACS developed during the fuel-efficient program (designated "advanced PACS" in ref. 5) was designed with the objective of providing flying qualities, at negative static margins as high as 10 percent, that were at least equivalent to those of the baseline aircraft (PACS off; AACS on) with a center-of-gravity position of  $0.25\bar{c}$ . (The  $0.25\bar{c}$  center-of-gravity position represents the existing L-1011 configuration with a positive static margin of approximately 14 percent (i.e., 14-percent static stability) and is considered to have satisfactory flying qualities.) The advanced PACS compensated for high Mach/high- $g$  instabilities that degrade the flying qualities during "upset" recoveries and maneuvers. This advanced PACS was not flight tested but was evaluated on the Langley Visual/Motion Simulator (VMS)—the handling qualities results are reported in reference 5.

The primary objective of the present study was to evaluate the effect of inserting combined time delays, pure and lagged, at three positions within the flight control system of the L-1011 math model with 10-percent negative static stability. The advanced PACS and AACS were both operative during category B (cruise) flight at Mach 0.83, at 33 000-ft altitude, and at a weight of 360 000 lbf. The effective time delay and pilot rating (opinion) are compared with those from the category C landing approach simulations of reference 2.

## Symbols and Abbreviations

Measurements and calculations were made in U.S. Customary Units, and all calculations are based on the airplane body axes.

$\bar{c}$

mean aerodynamic chord, ft

$F_c$	column force, lbf
$g$	acceleration due to gravity ( $1g = 32.17 \text{ ft/sec}^2$ )
$K_3$	combined pitch-attitude/velocity gain
$K_{FF}$	feedforward gain
$K_{nz}$	normal-acceleration gain
$K_q$	pitch-rate damper gain
$K_s$	column feel-spring gradient, lbf/in.
$K_x$	calculated gain for advanced PACS
$M$	Mach number
$n_z$	normal acceleration
$q$	pitching angular velocity, deg/sec
$\bar{q}$	dynamic pressure, lbf/ft <sup>2</sup>
$s$	Laplace transform operator
$t$	time, sec
$t_1$	intersection of pitch-rate-response maximum-slope tangent line and zero-amplitude line (effective time delay), sec
$\alpha$	angle of attack, deg
$\delta_c$	total column deflection, in.
$\delta_{col}$	software stick position, in.
$\delta_e$	elevator deflection
$\delta_f$	flap deflection
$\delta_{HT}$	horizontal-tail deflection, deg
$\delta_{HT}^*$	modified horizontal-tail feedback signal for secondary gain scheduling (function of $\alpha$ , $\phi$ , and $M$ )
$\theta$	pitch attitude, deg
$\tau$	time constant, sec
$\tau_1$	numerator time constant of lag-lead transfer function
$\tau_2$	denominator time constant of lag-lead transfer function
$\tau_c$	force sensor filter time constant
$\phi$	angle of roll, deg

①, ①a, FCS locations shown in figure 4

②, ③

#### Subscripts:

col	column
com	command
max	maximum
$o$	output
$p$	pilot
str	stretch
trim	trimmed flight

#### Abbreviations:

AACS	aileron active control system
FCS	flight control system
flt	flight
g-b	ground based
MTC	Mach trim compensation
PACS	pitch active control system
PR	pilot rating
RSS	relaxed static stability
ref.	reference
SAS	stability augmentation system
VMS	Langley Visual/Motion Simulator

### Description of Simulated Airplane

The baseline simulation is a nonlinear six-degree-of-freedom model of a modified version of the Lockheed L-1011 airplane developed during energy-efficient transport studies at the Langley Research Center. The L-1011 is a current generation, subsonic, commercial transport airplane (fig. 1). The airplane is powered by three Rolls-Royce RB, 211-22B high-bypass-ratio turbofan engines and has a flying stabilizer with a geared elevator. Airplane geometry and weight data are presented in table I.

The simulated L-1011 uses the elevator and stabilizer for longitudinal control, the outboard ailerons and spoilers for lateral control, and the rudder for directional control. The basic longitudinal control system includes servoactuator, cable stretch, and position and rate-limiter modeling. The lateral-directional control system was the same as reported in reference 2.

Aircraft lateral control is achieved by the basic lateral control system, which determines aileron and spoiler deflections and includes servoactuator and position-limiter modeling. Only the four outboard spoiler panels (each wing) were modeled for lateral control.

Aircraft directional control is achieved by the directional control system, which determines manual and SAS contributions to the rudder position. The directional SAS consists of a yaw damper that includes aileron input, servoactuator, and rate- and position-limiter modeling for improved turn coordination.

Although the subject simulation study utilized six-degree-of-freedom equations of motion (with nonlinear aerodynamic and thrust input data), the lateral-directional flight characteristics are not addressed in this paper because this was a study of "longitudinal" handling qualities.

## Description of Simulation Equipment

The simulation study was made with the general-purpose cockpit of the Langley Visual/Motion Simulator (VMS), a ground-based motion simulator with six degrees of freedom. For this study the VMS had a transport-type cockpit equipped with conventional flight and engine-thrust controls and with a flight-instrument display representative of those found in current transport airplanes. (See fig. 2.) Instruments that indicated angle of attack, angle of sideslip, flap angle, horizontal stabilizer angle, and column force were also provided.

The control forces on the wheel, column, and rudder pedals were provided by a hydraulic system coupled with an analog computer. The system incorporated variable-feel characteristics of stiffness, damping, coulomb friction, breakout forces, detents, and inertia.

The average total motion delay of the VMS, including computational throughput, is less than 60 msec and is quite compatible with the rest of the system, including visual delays. The washout system used to present the motion-cue commands to the motion base is nonstandard. It was conceived and developed at the NASA Langley Research Center (ref. 6). The basis of the washout is the continuous adaptive change of parameters to (1) minimize a cost function through continuous steepest descent method and (2) produce the motion cues in translational accelerations and rotational rates within the motion envelope of the synergistic base. The only aural cue provided was engine noise.

## Tests and Procedures

Two experienced pilots flew simulated up-and-away flights over a 2-week period with emphasis on the high-speed cruise configuration. A total of 137 flights were "flown" under both calm and turbulent air conditions to investigate the effects of time

delay in the longitudinal axis. Both pure and first-order lag forms of time delay were investigated.

The cruise task consisted of several pitch and roll attitude changes, airline operational turns, and wind-up turns. Reference 5 is an evaluation of the longitudinal handling qualities with pilot ratings and comments on the flying qualities of a simulated L-1011 transport aircraft and of the effects of advanced stability and control augmentation systems on these characteristics. (See fig. 3 for PACS used in this study.) Since the current trend in aircraft design is toward unstable or marginally stable, highly augmented configurations, the purpose of this test was to investigate the effects of time delay in such control systems.

## Results and Discussion

In order to compare the experimental results of the present tests with the present Military Flying Qualities Specifications (ref. 1), the pilot-opinion data (viz, ratings) were plotted versus effective time delay. All fairings to the data were obtained using linear least-squares curve-fitting techniques. The input time delays were converted to effective time delays by the method of reference 7. The effective time delay  $t_1$  is measured from the instant of the controller force step input to the time corresponding to the intersection of the tangent to the maximum slope and the zero-amplitude axis. The effects of the time delay were evaluated at the pilot input (1), the PACS input (2), and just downstream of the summer (3). (See fig. 4.) In cases where time delay was inserted at location (1), pilot's column input, an equivalent amount of time delay was also input at the longitudinal trim (1a) to prevent the pilot from flying the airplane strictly with the trim button.

Figure 5 was derived from time-history responses in pitch rate of the simulation model to control unit step inputs and was used to convert first-order lags to effective time delays in the longitudinal control axis. (An inherent 0.047 sec of pure (digital) delay is accounted for in the fig. 5 effective delays.) Figures 6(a) and 6(b) present pilot rating (see table II) as a function of longitudinal control effective time delay  $t_1$  for pilots 1 and 2 in turbulent air, and figures 6(c) and 6(d) present similar data for calm-air conditions. The delay is at FCS locations (1) and (1a). The subscripted numbers shown at the plotted data points indicate multiple points. Figures 7(a) and 7(b) present pilot rating versus effective time delay for pilots 1 and 2 in turbulent air, and figures 7(c) and 7(d) present similar data for calm-air conditions. The delay is at

PACS input (2). Figures 8(a) and 8(b) present pilot rating versus effective time delay for pilots 1 and 2 in turbulent air, and figures 8(c) and 8(d) present similar data for calm-air conditions. The delay is at FCS location (3). The average pilot ratings at each delay location are plotted against effective time delay for turbulent conditions and calm-air conditions in figures 9(a) and 9(b). From these averaged pilot rating data, maximum allowable time delays were tabulated for various flying-qualities levels and are presented in table III.

It is evident from the data of figure 9 and table III that the source of the time delay in the control system may determine the degree of handling-qualities degradation. These data indicate that if the time-delay source is at the pilot input locations (FCS locations (1) and (1a)), a substantial level of time delay is allowed before there is significant degradation in flying qualities. An effective time delay greater than 0.31 sec was required before the flying qualities degraded into the level-2 region, and indications are that a  $\tau_1 > 1.4$  sec would be required before level-3 flying qualities would be experienced. As may be expected, time-delay locations (2) and (3) were the most critical, because the simulated airplane was inherently unstable and therefore relied on the PACS for stability.

Comparison of the maximum allowable time delay from these tests with those of the reference 1 specifications shows that, with the time delay in even the most critical location of the FCS (i.e., location (3)), the present specifications (ref. 1) appear to be too stringent for large aircraft. Also, the trends of time-delay effects at FCS location (3) for the statically unstable airplane of the present study at cruise flight conditions are similar to those noted in the low-speed approach and landing tests of a statically stable airplane reported in reference 2. The maximum allowable time delay for level-1 handling qualities is 0.17 sec (fig. 9) and 0.15 sec (ref. 2), respectively, as opposed to the 0.10 sec specifications of reference 1.

A brief portion of this simulation study was devoted to investigating the possibility of reducing the adverse effects of FCS time delays through variations in the control sensitivity. (In this instance, control sensitivity is defined as the magnitude of the column-to-stabilizer gearing.) Figure 10 presents typical results from one pilot with variations in control gearing for a configuration with an effective time delay of 0.36 sec. Indications are that a control-gearing to baseline-gearing ratio of approximately 1.25 improves the flying qualities for the calm-air condition to level 1 and that, for the turbulent condition, the

flying qualities were improved from level 3 to level 2. However, any further increase in gearing degrades the flying qualities significantly. These results are in agreement with the findings of reference 8, which showed a strong correlation between control sensitivity and time-delay effects in closed-loop piloting tasks. These findings may be significant, because they suggest that if an increase in FCS time delay is experienced as the result of a failure in the control system, compensation may be possible through variations in control gearing (if available to the pilot). A degree of fault tolerance could thus be provided.

## Concluding Remarks

Results of this piloted simulation study verify previous findings which show that the present military specifications for allowable control-system time delay may be too stringent when applied to transport-size aircraft. Also, the degree of handling-qualities degradation due to time delay is strongly dependent on the source of the time delay in an advanced flight control system. The specification of maximum allowable time delay for each specific source of time delay in the control system, in addition to less stringent overall maximum level of time delay, should be considered for large aircraft. Preliminary results also suggest that adverse effects of control-system time delay may be at least partially offset by variations in control gearing.

It is evident that a much larger data base needs to be generated for determining control-system time-delay limits for large transport aircraft. This data base should include different aircraft baselines, control systems, and piloting tasks (flight phases) with many pilots participating. A reasonable set of limits for control-system time delay could thus be established to substitute for the military specification limits currently being used.

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July 23, 1987

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Table I. Airplane Geometry and Weight Data

Wing:	
Reference area, ft <sup>2</sup> . . . . .	3456
Reference mean aerodynamic chord, ft <sup>2</sup> . . . . .	24.46
Span, ft . . . . .	164.33
Aspect ratio . . . . .	7.814
Leading-edge sweep, deg . . . . .	35
Horizontal tail:	
Area, ft <sup>2</sup> . . . . .	1282
Span, ft . . . . .	71.58
Aspect ratio . . . . .	4.0
Leading-edge sweep, deg . . . . .	35
Vertical tail:	
Area, ft <sup>2</sup> . . . . .	550
Span, ft . . . . .	29.67
Aspect ratio . . . . .	1.6
Leading-edge sweep, deg . . . . .	35
Weight:	
Maximum ramp, lbf . . . . .	424 000
Maximum takeoff, lbf . . . . .	422 000
Maximum landing, lbf . . . . .	358 000
Cruise at 33 000 ft ( $M = 0.83$ ), lbf . . . . .	360 000
Zero fuel, lbf . . . . .	312 460
Operating empty, lbf . . . . .	261 000

Table II. Pilot Rating System

PR			
<p>CONTROLLABLE</p> <p>Capable of being controlled or managed in context of mission, with available pilot attention.</p>	<p>ACCEPTABLE</p> <p>May have deficiencies which warrant improvement, but adequate for mission.</p>	<p>SATISFACTORY</p> <p>Meets all requirements and expectations; good enough without improvement.</p>	1
		<p>Clearly adequate for mission.</p>	2
		<p>Reluctantly acceptable. Deficiencies which warrant improvement. Performance adequate for mission with feasible pilot compensation.</p>	3
	<p>UNACCEPTABLE</p> <p>Deficiencies which require improvement. Inadequate performance for mission even with maximum feasible pilot compensation.</p>	<p>UNSATISFACTORY</p>	4
			5
			6
	<p>UNCONTROLLABLE</p> <p>Control will be lost during some portion of mission.</p>		7
			8
			9
			10

Table III. Summary of Maximum Allowable Time Delay—Longitudinal Axis and Cruise Flight

(a) Turbulent air

Flying- qualities  level	Delay location			MIL-F-8785C  (ref. 1)
	① and ①a	②	③	
	Allowable delay, sec			
1	0.31	0.18	0.17	0.10
2	>1.40	.64	.48	.20
3		>.90	.74	.25

(b) Calm air

Flying- qualities  level	Delay location			MIL-F-8785C  (ref. 1)
	① and ①a	②	③	
	Allowable delay, sec			
1	0.87	0.46	0.30	0.10
2	>1.40	>1.40	.76	.20
3			1.13	.25

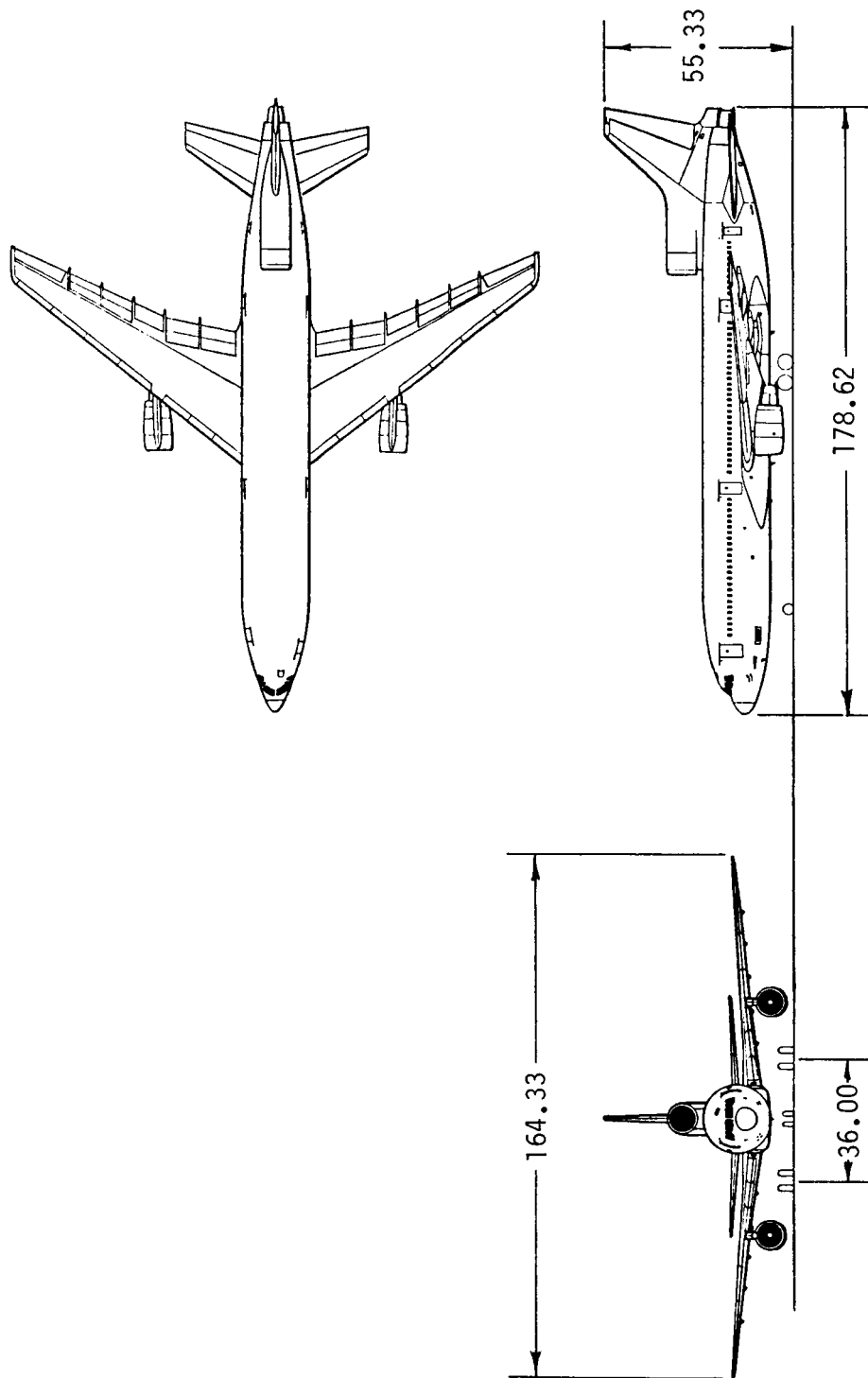
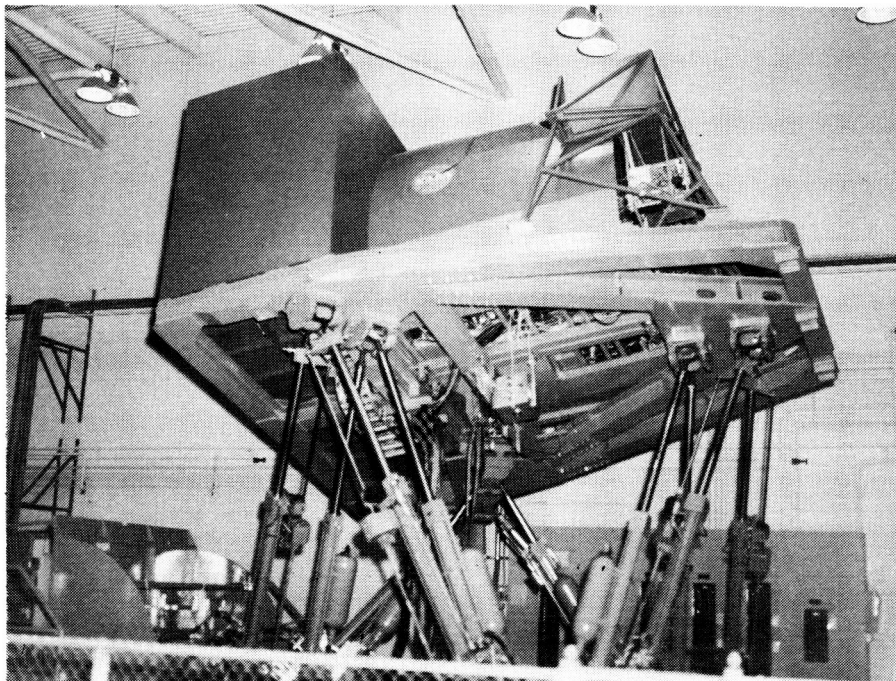


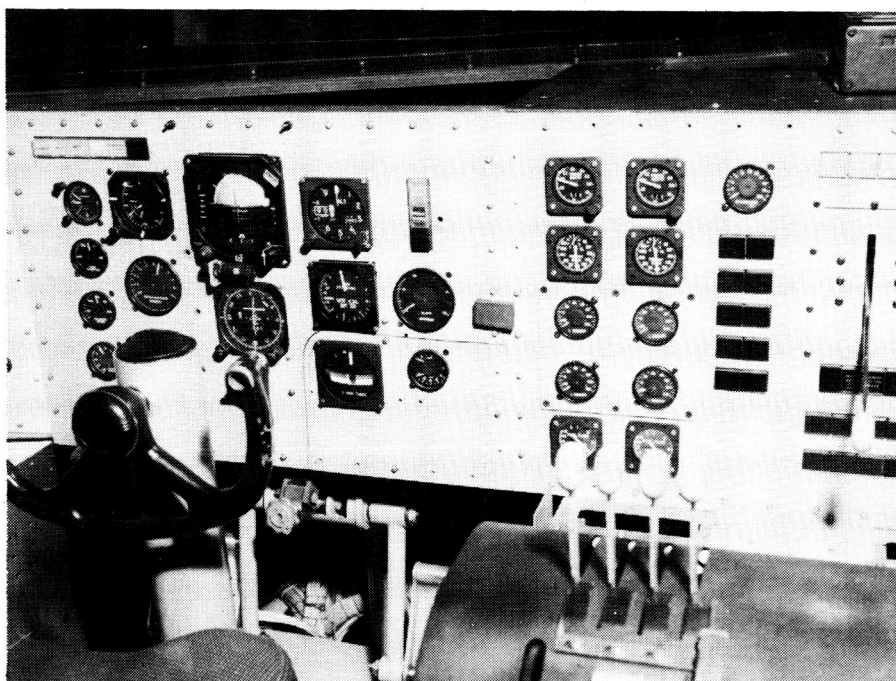
Figure 1. Three-view sketch of simulated Lockheed L-1011 airplane. All dimensions indicated are in feet.

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(a) Langley Visual/Motion Simulator.



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(b) Instrument panel.

Figure 2. Langley Visual/Motion Simulator and instrument panel display.

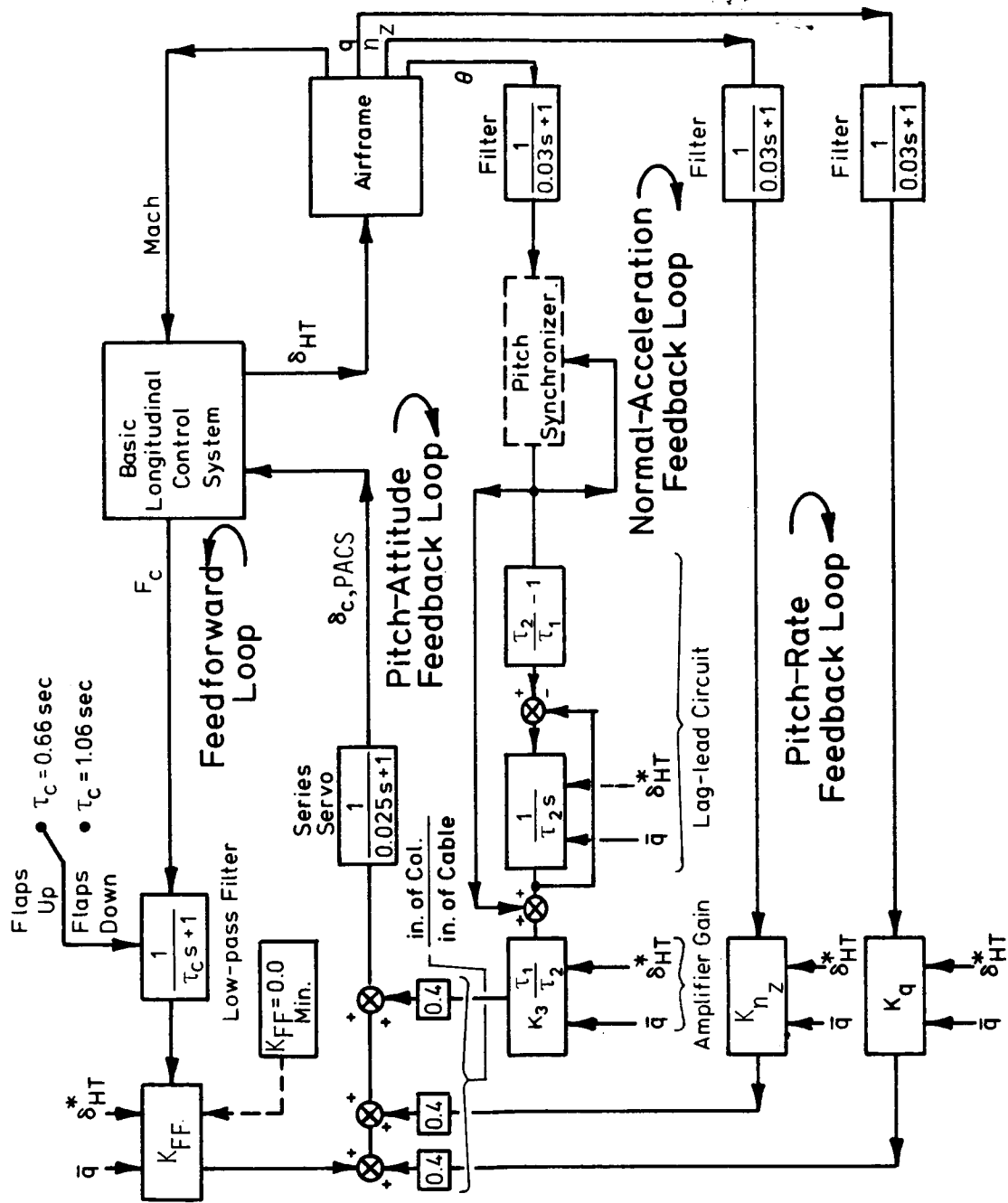


Figure 3. Analytical block diagram of advanced PACS.

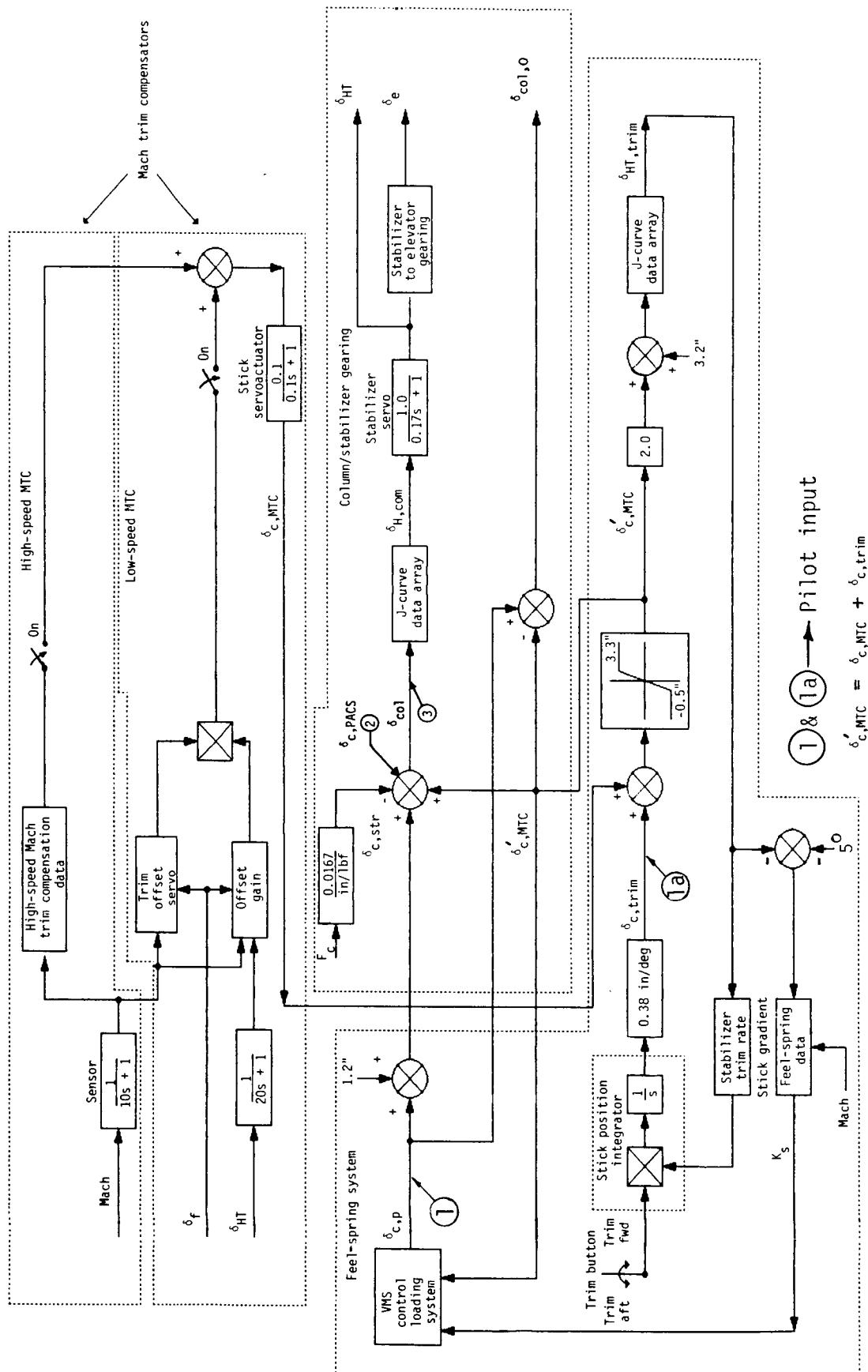


Figure 4. Longitudinal control system block diagram.

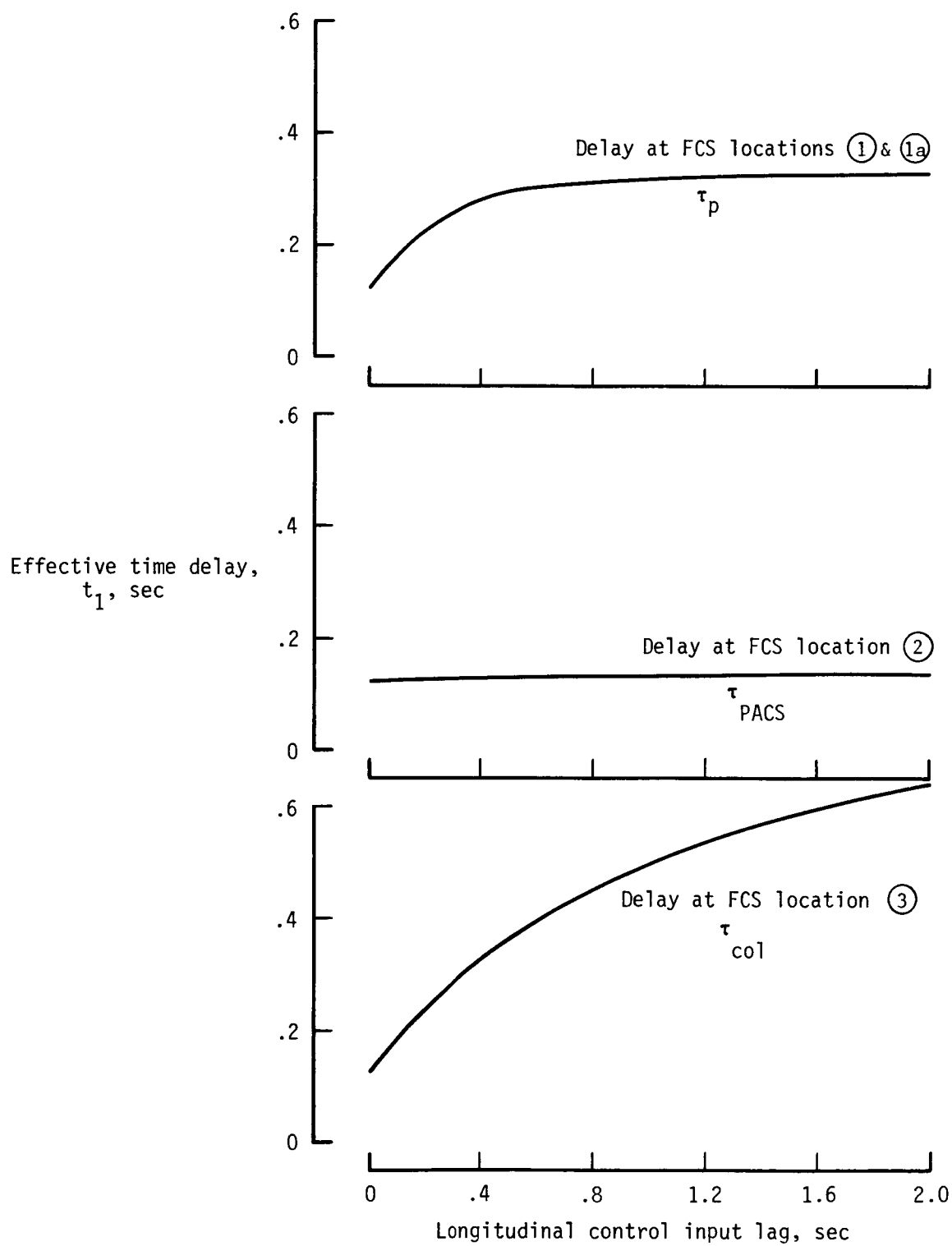
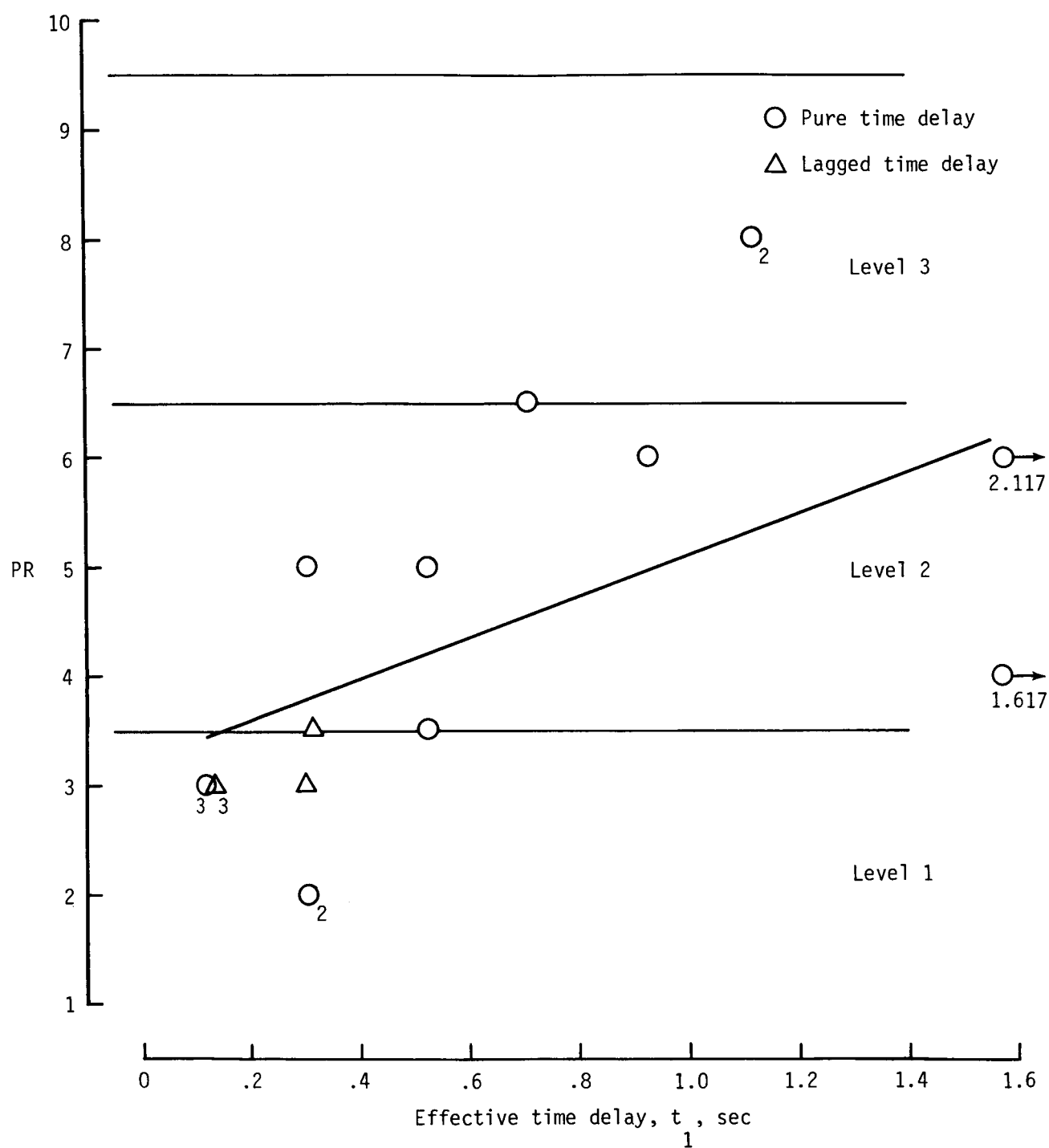
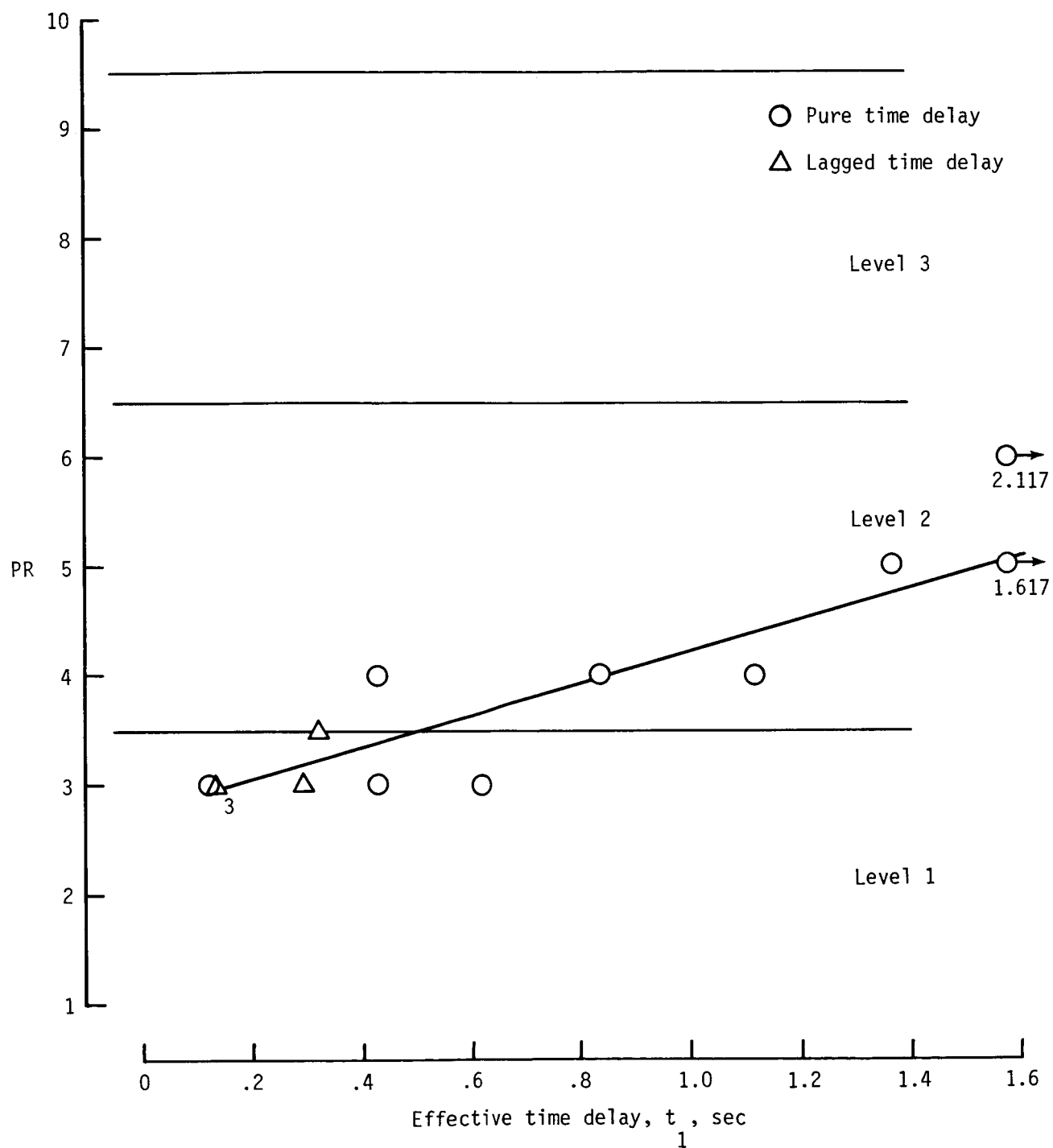


Figure 5. Conversion from lagged longitudinal control inputs to effective time delay.



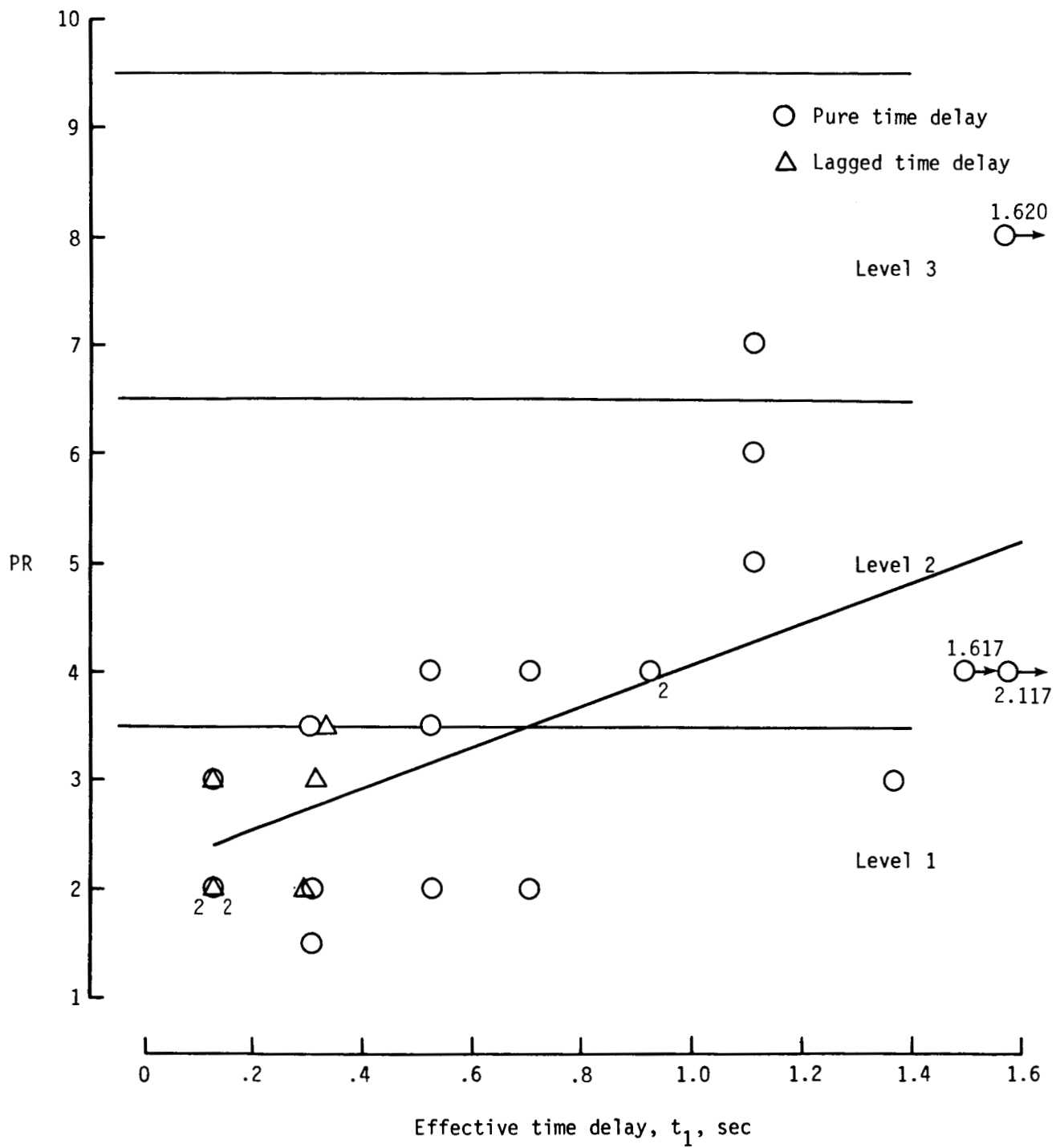
(a) Turbulence, pilot 1.

Figure 6. Pilot rating as a function of longitudinal control effective time delay. Delay at FCS location (1) and (1a).



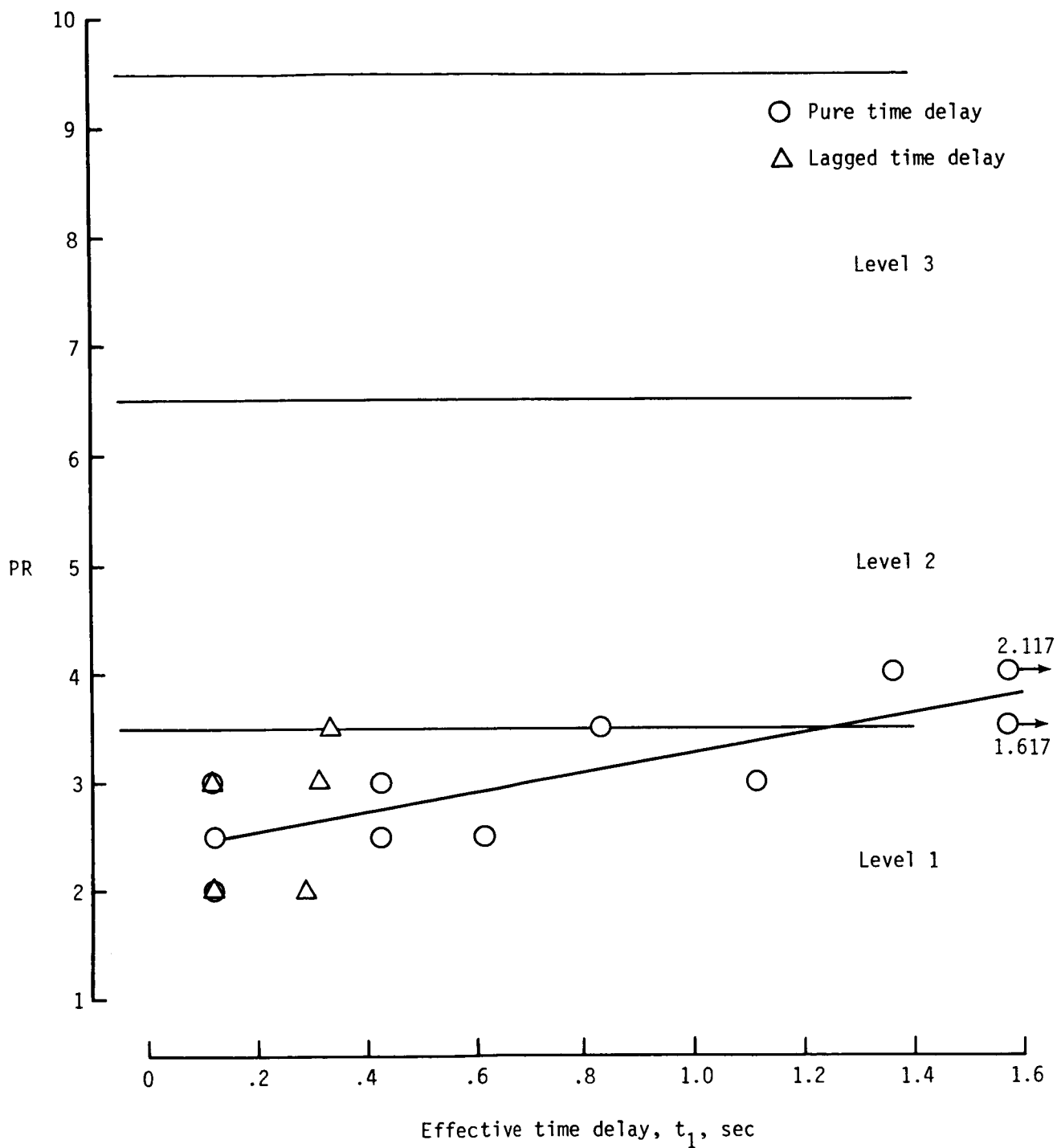
(b) Turbulence, pilot 2.

Figure 6. Continued.



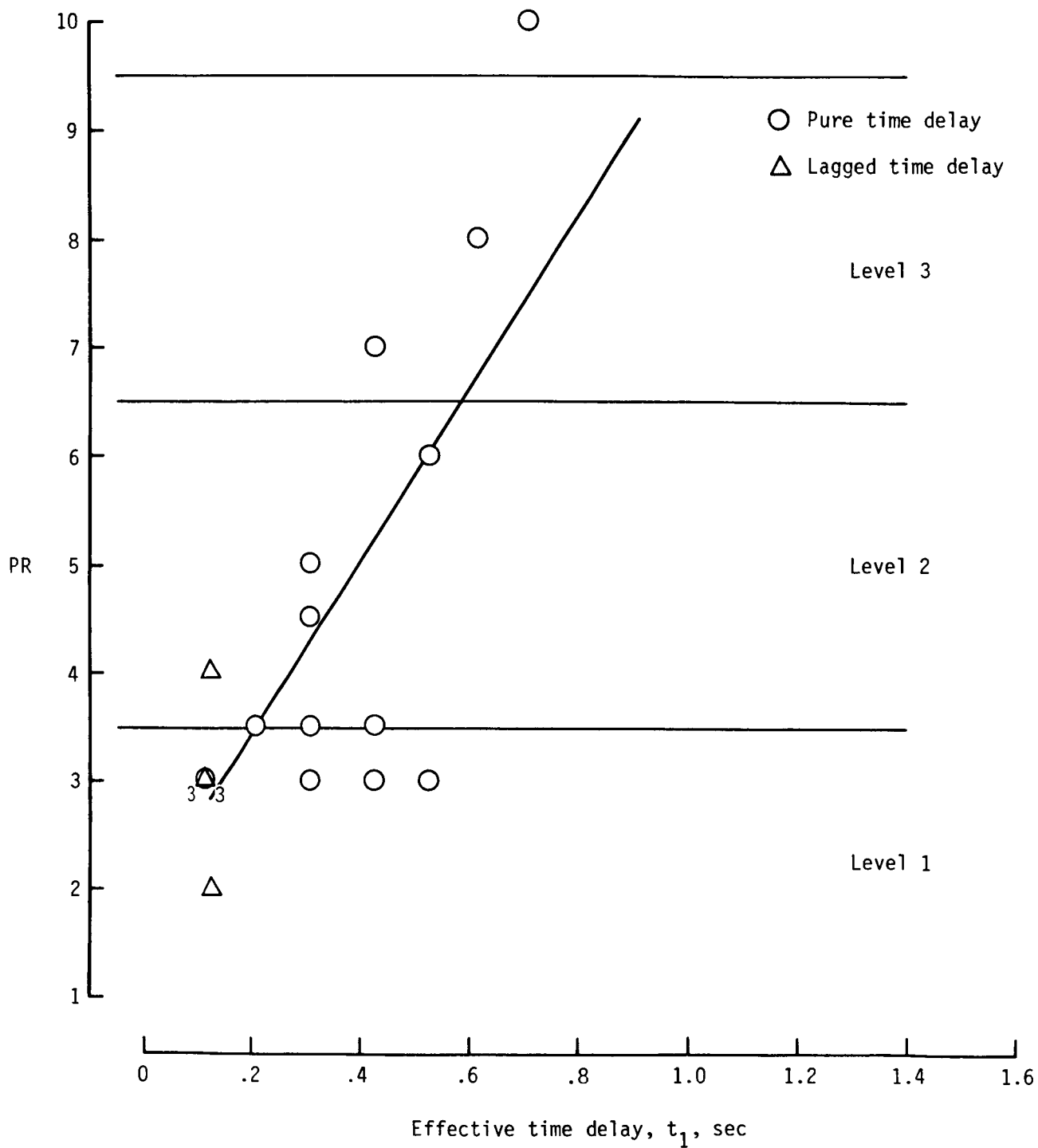
(c) Calm air, pilot 1.

Figure 6. Continued.



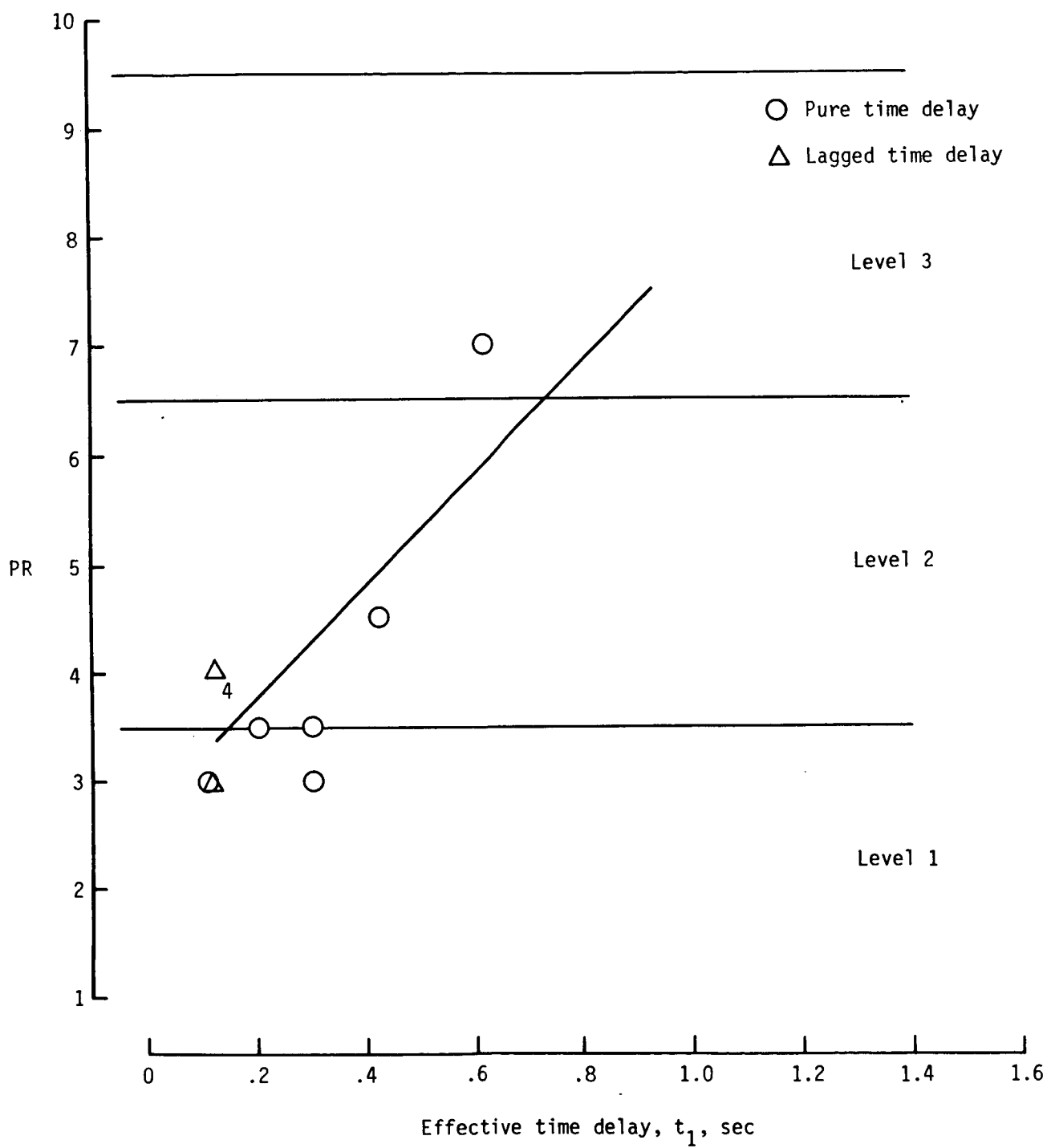
(d) Calm air, pilot 2.

Figure 6. Concluded.



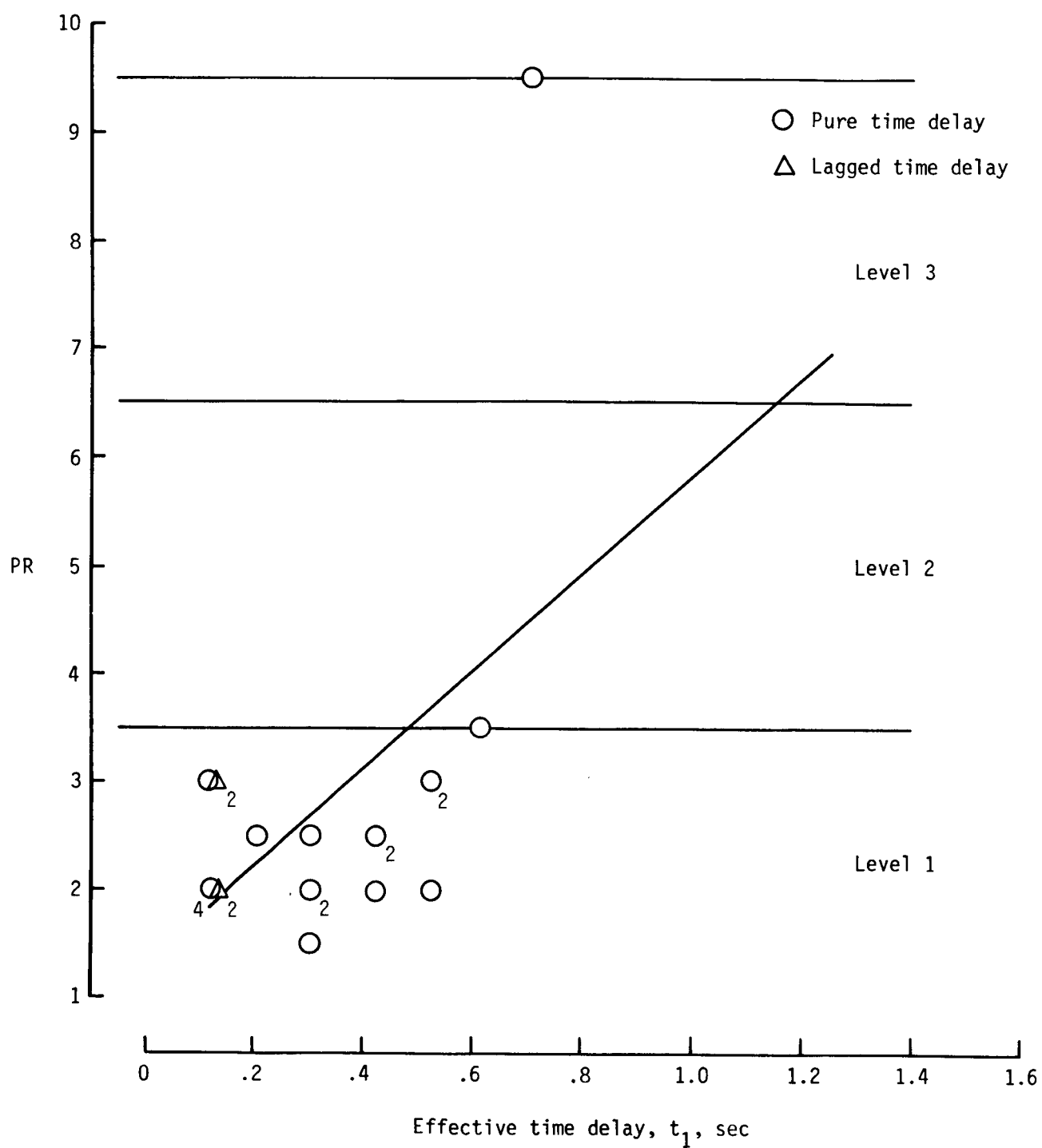
(a) Turbulence, pilot 1.

Figure 7. Pilot rating as a function of longitudinal control effective time delay. Delay at FCS location (2).



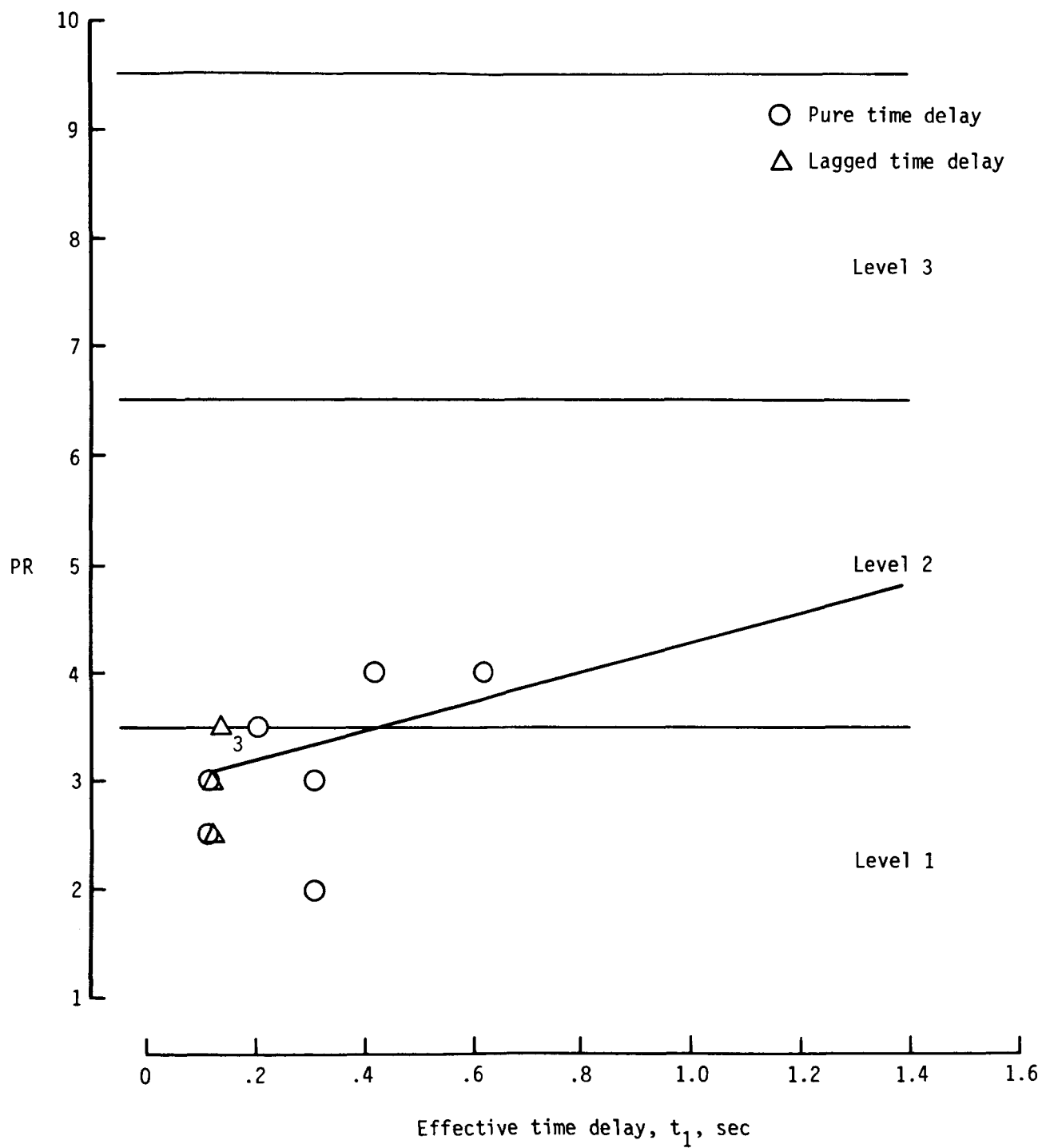
(b) Turbulence, pilot 2.

Figure 7. Continued.



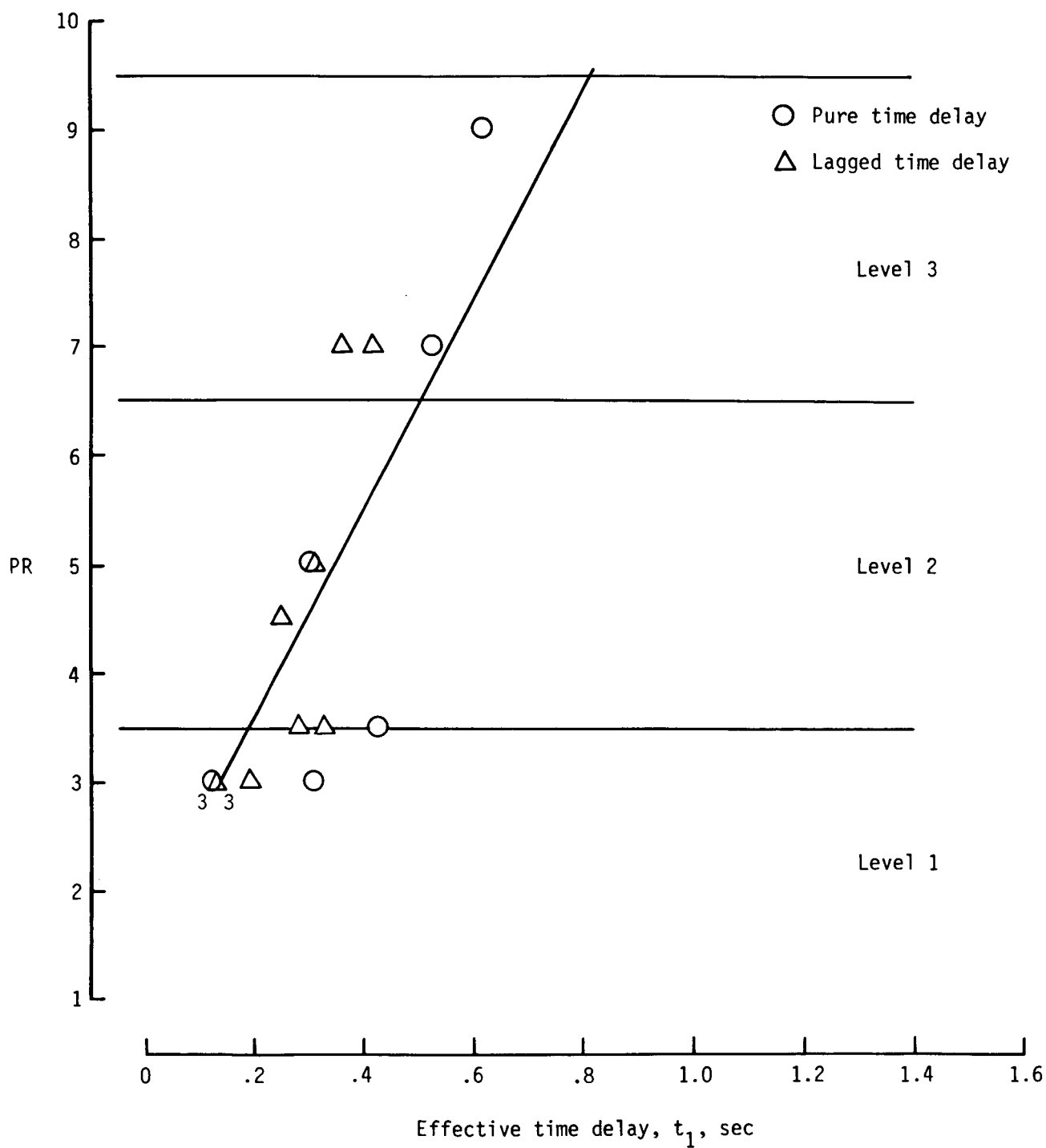
(c) Calm air, pilot 1.

Figure 7. Continued.



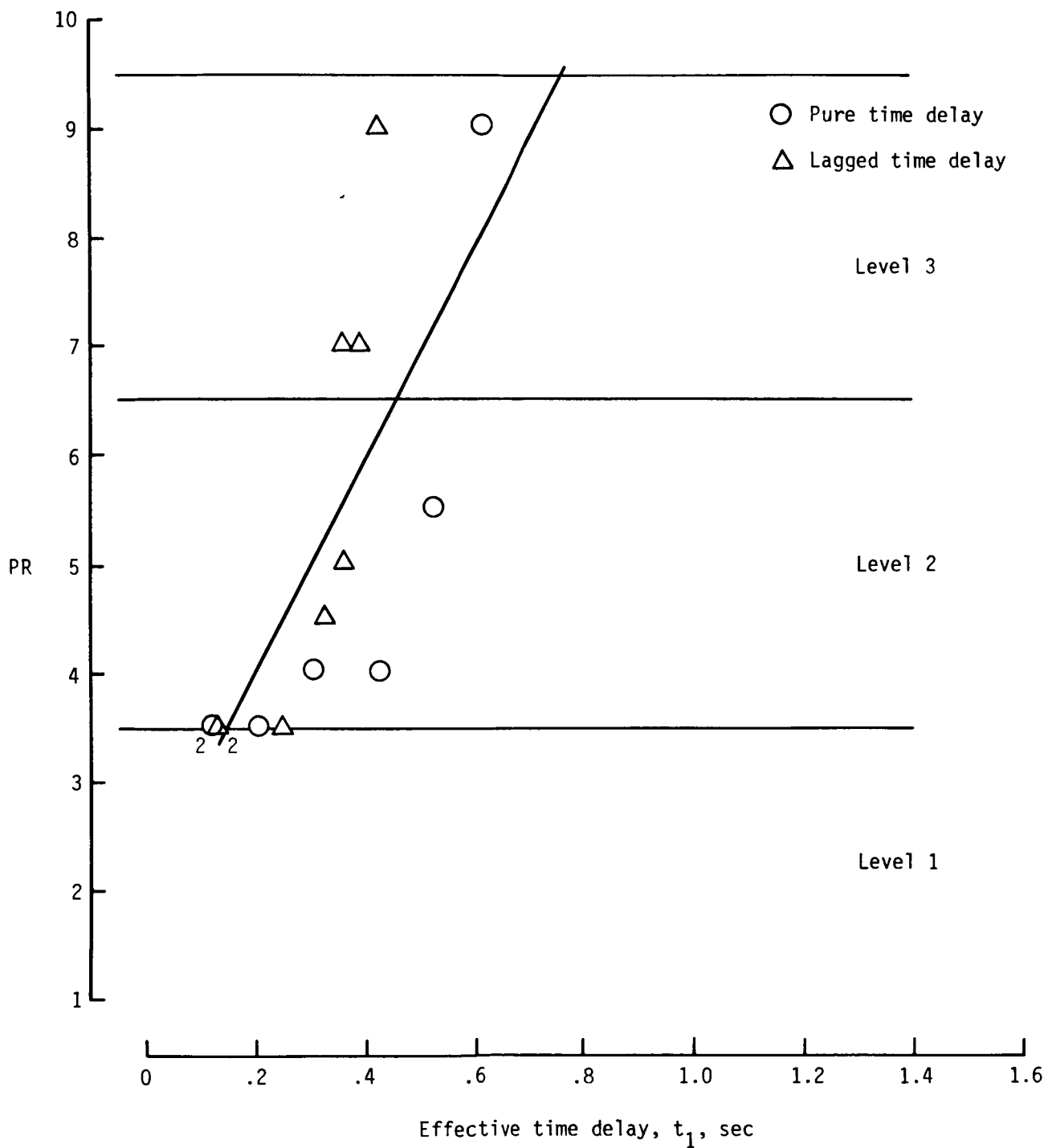
(d) Calm air, pilot 2.

Figure 7. Concluded.



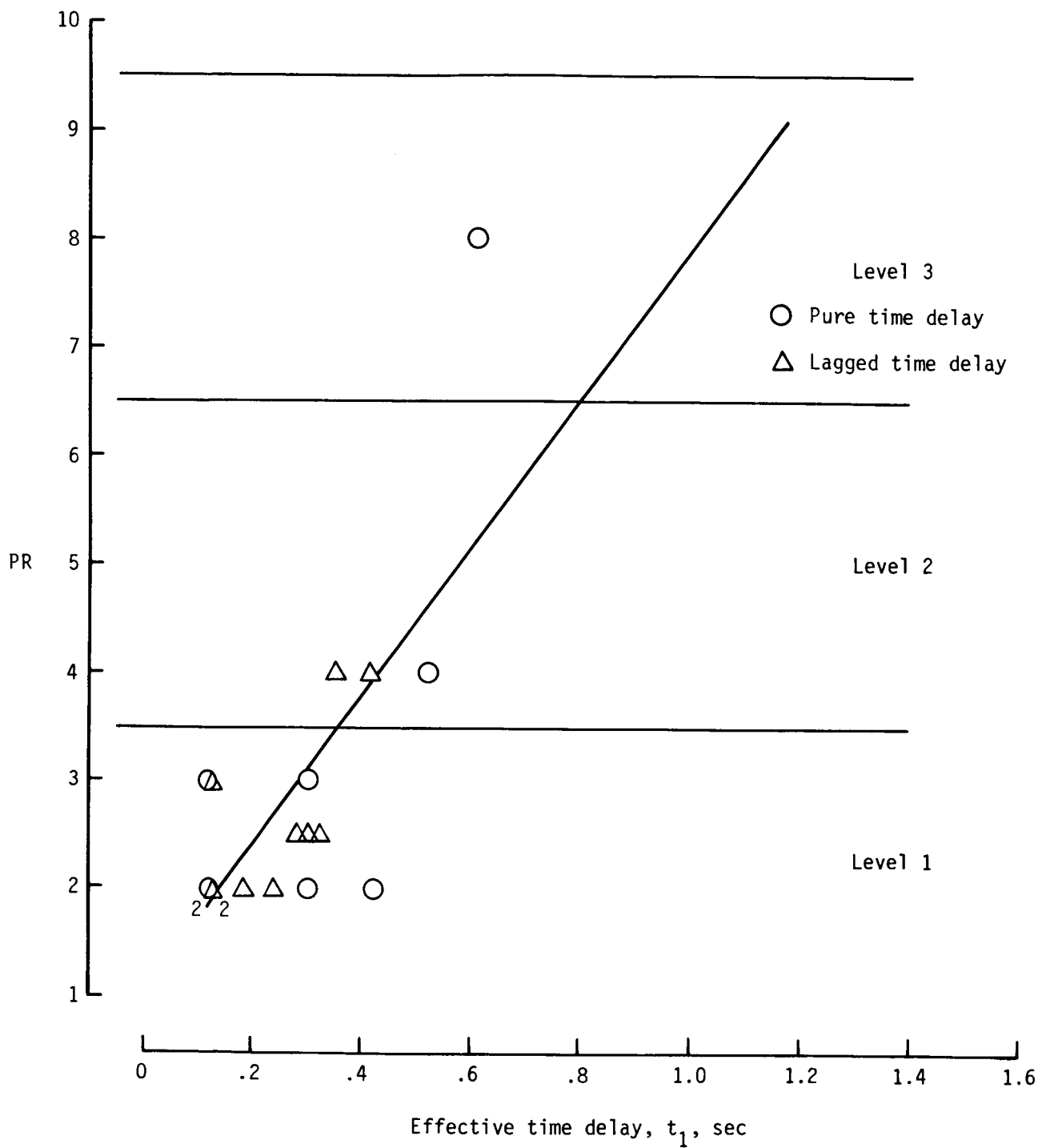
(a) Turbulence, pilot 1.

Figure 8. Pilot rating as a function of longitudinal control effective time delay. Delay at FCS location ③.



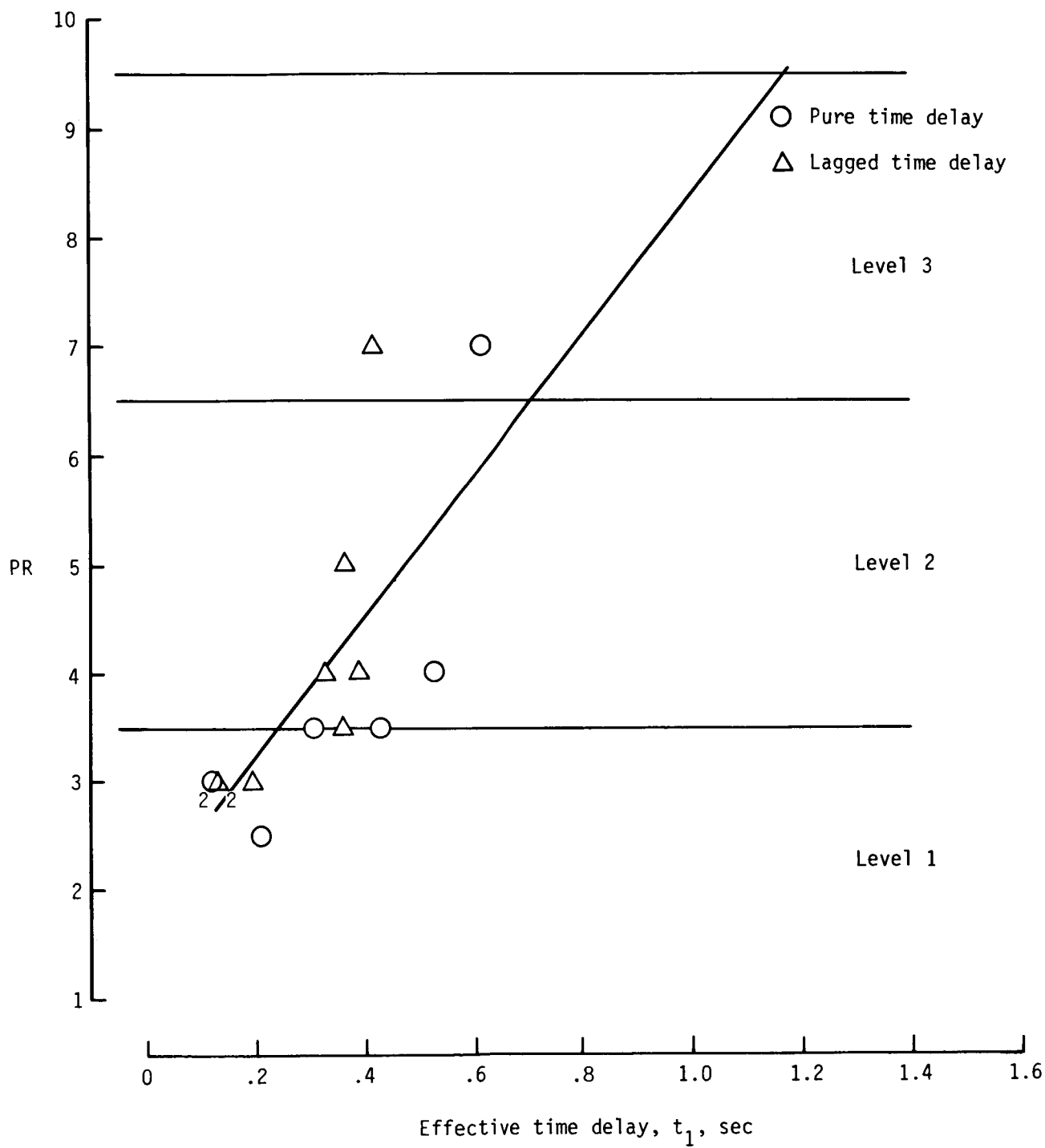
(b) Turbulence, pilot 2.

Figure 8. Continued.



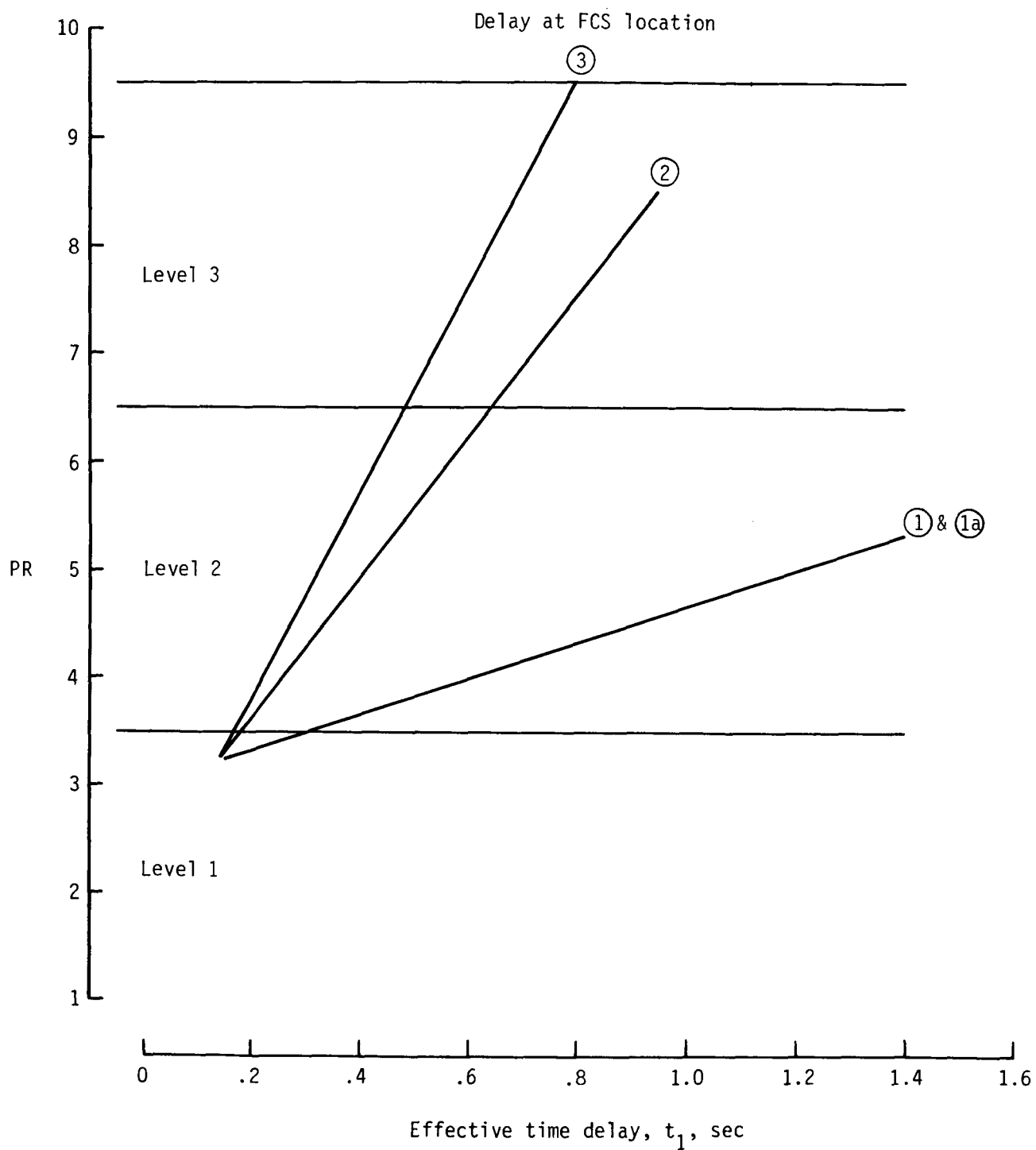
(c) Calm air, pilot 1.

Figure 8. Continued.



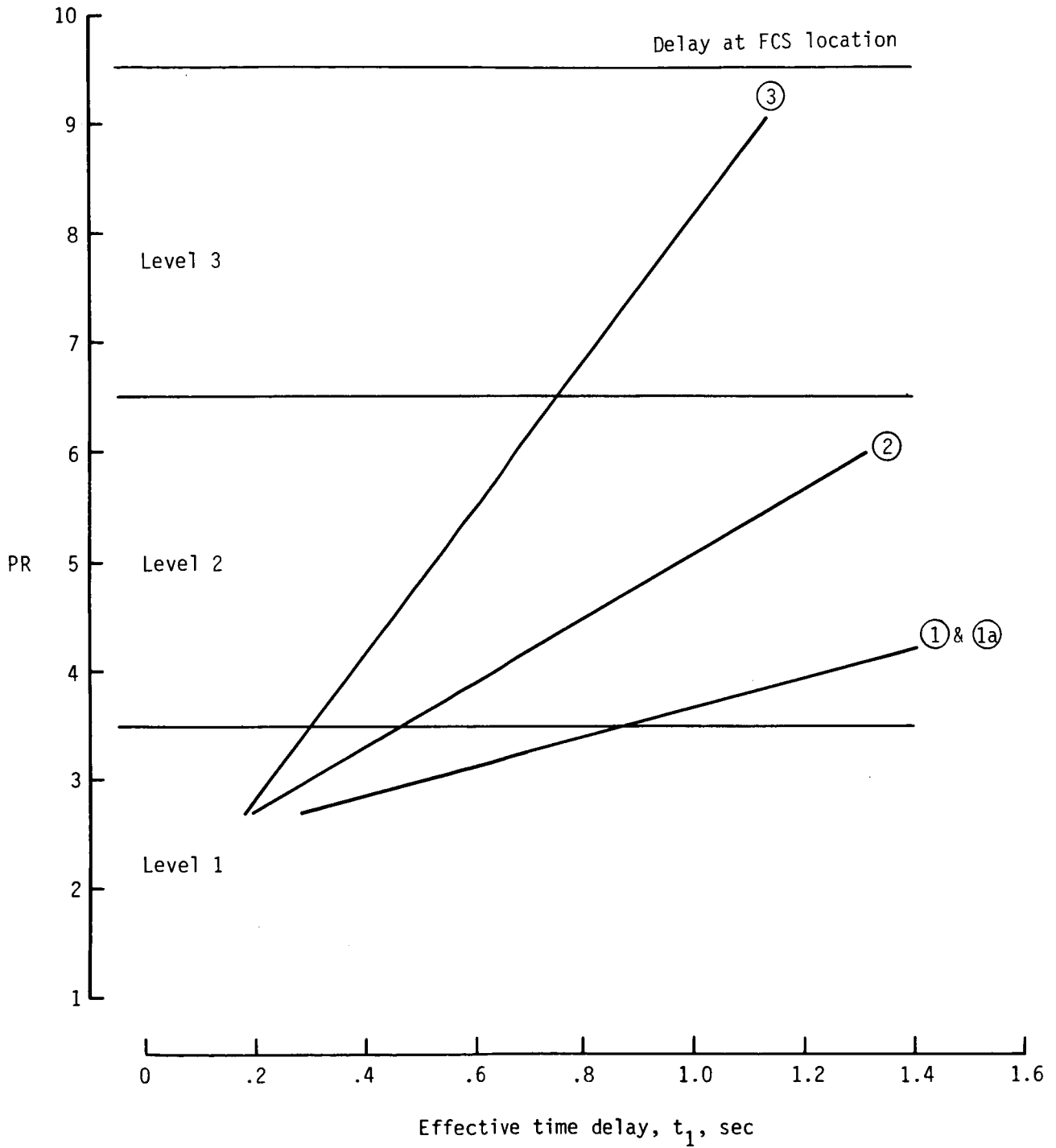
(d) Calm air, pilot 2.

Figure 8. Concluded.



(a) Turbulent conditions.

Figure 9. Effect on pilot rating of time delay by pilot's input in the longitudinal control system. (Pilot ratings are the average of the participating pilots.)



(b) Calm-air conditions.

Figure 9. Concluded.

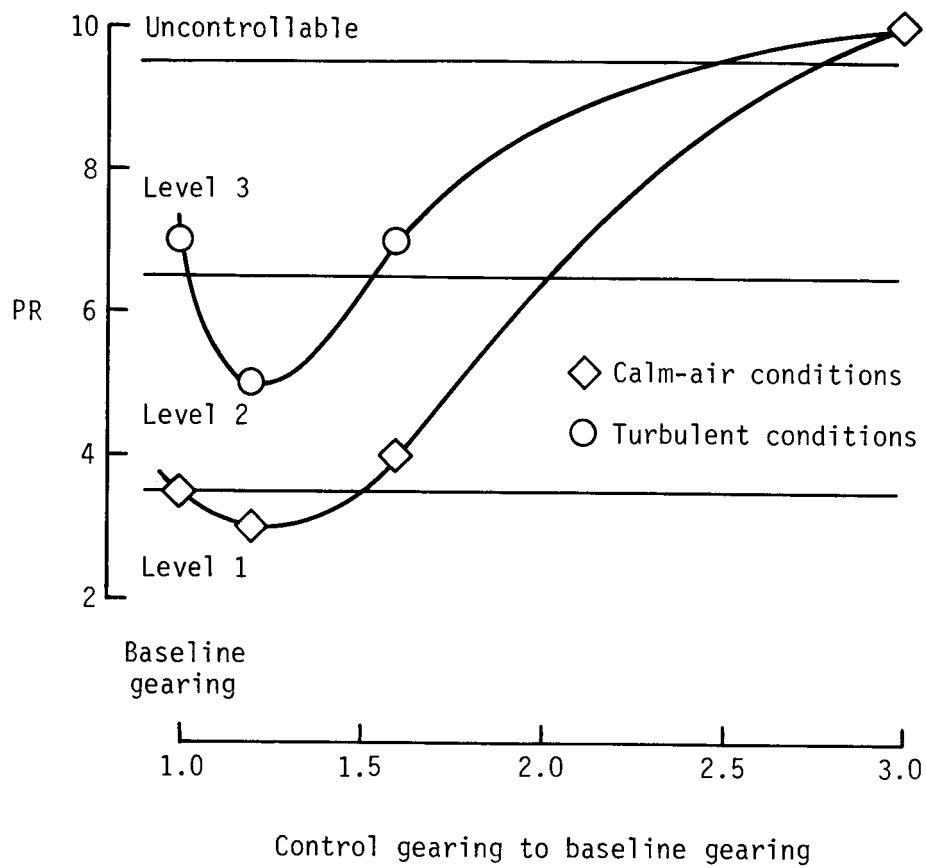


Figure 10. Indication of effect of control gearing on pilot rating. Delay at FCS location ③ ;  $t_1 = 0.36$  sec; pilot 2.

# Report Documentation Page

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16. Abstract A piloted simulation study was conducted to determine the permissible time delay in the flight control system of a 10-percent statically unstable transport airplane during cruise flight conditions. The math model used for the simulation was a derivative Lockheed L-1011 wide-body jet transport. Data were collected and analyzed from a total of 137 cruising flights in both calm- and turbulent-air conditions. Results of this piloted simulation study verify previous findings that show present military specifications for allowable control-system time delay may be too stringent when applied to transport-size airplanes. Also, the degree of handling-qualities degradation due to time delay shown to be strongly dependent on the source of the time delay in an advanced flight control system. Specification of maximum allowable time delay for each specific source of time delay in the control system, in addition to a less stringent overall maximum level of time delay, should be considered for large aircraft. Preliminary results also suggest that adverse effects of control-system time delay may be at least partially offset by variations in control gearing. A much larger data base is needed for large-transport control studies. Thus, it is recommended that the data base included different airplane baselines, control systems, and piloting tasks with many pilots participating, so that a reasonable set of limits for control-system time delay can be established to replace the military specification limits currently being used.					
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